

## Resonant converter

The invention relates to a resonant converter.

In converters of this type a d-c voltage carried on the input side is first chopped and the a-c voltage thus produced in the form of a chopped d-c voltage is processed by means of circuit parts containing resonant circuit elements.

5               Transformers, particularly ones that produce an electrical separation of the input and output side of the converter, are used for this purpose. With converters of this type it is possible to manufacture inexpensive, small, lightweight power supply units/ switched-mode power supplies, which can advantageously be used in consumer electronics appliances such as set top boxes, satellite receivers, television sets, computer monitors, video recorders  
10              and compact audio systems. In these applications there is often a need for converters that generate multiple output voltages on multiple converter outputs from one input d-c voltage.

The object of the invention is to design a resonant converter having multiple outputs, two of which are adjustable separately from one another, that is as cost-effective as possible.

15              The object is achieved in that the converter has multiple outputs and contains a transformer having a primary winding and at least two secondary windings with different winding directions.

With this approach it is possible to provide a converter, which has only one diode (power semiconductor element) in each branched output coupled to a secondary  
20              winding; the number of diodes needed in the branched outputs is therefore reduced to a minimum. Two output voltages or output currents generated from one input voltage can be adjusted separately from one another and therefore adjusted to preset values with improved tolerances compared to conventional resonant converters; the converter according to the invention is moreover capable of generating multiple preset output voltages and one or more  
25              preset output currents simultaneously. Furthermore, a more cost-effective transformer can be used over a wide output voltage range, since the groups of secondary windings with different winding directions may have different ratios of output voltage generated to number of turns in the associated secondary winding.

If the transformer has a first group of secondary windings with one or more secondary windings having a first winding direction and a second group of secondary windings with one or more secondary windings having a second winding direction, secondary windings can be electrically separated from one another or electrically coupled to one another, the secondary windings in the latter case being coupled, in particular, to a ground potential. The secondary windings may be connected in series, tapings then being provided between the secondary windings.

The resonance frequency of the resonant converter is determined by inductive and capacitive elements of the resonant converter, which take the form of one or more capacitors and/or coils and the transformer main inductance together with the transformer leakage inductances. The resonant frequency of the converter can be adjusted to the desired value, in particular, through additional separate coils, even where this value cannot be set solely by means of a specific transformer design having a preset main inductance and preset leakage inductances.

In one embodiment of the resonant converter, switching elements are used to chop an input d-c voltage and a feedback loop with a regulating circuit serves for regulating two output voltages. Here the frequency and the duty cycle of the chopped input d-c voltage are provided as regulating control variables, it being sufficient to provide a measuring signal for the regulating circuit from just one of the associated output voltages for just one group of identically-wound secondary windings at a time. In the case of the converter according to the invention it is sufficient to couple each of the secondary windings of the transformer to the converter outputs by way of one diode and one output filter each. In particular, different ratios of output voltage to number of turns can be provided in respect of associated secondary windings having different winding directions, so that the distribution of the overall output power generated by the converter can be influenced by presetting these ratios accordingly. At the same time a further converter output voltage range is feasible using simple transformer designs.

The invention will be further described with reference to examples of embodiments shown in the drawings, to which, however, the invention is not restricted. In the drawings:

Fig.1 shows a resonant converter having two outputs,

Fig.2 shows a half-bridge circuit for the resonant converter,

Figs.3A, 3B and 3C show various output filters for the resonant converter,

Fig.4 shows an equivalent circuit diagram for the resonant converter,  
Fig.5 to Fig.7 show voltage and current characteristics in the resonant  
converter,

Fig.8 to Fig.10 show various embodiment options for a resonant converter,  
5 according to the invention

Fig.11 shows an example of the coupling of converter outputs to the regulating  
circuit of the resonant converter and

Fig.12 shows a block diagram for a design variant of the regulating circuit of  
the resonant converter.

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The circuit arrangement shown in Fig.1 shows a resonant converter 1 having  
an inverter 2, which is here designed as chopper and converts a d-c voltage (not shown) into  
an a-c voltage, i.e. in this case a chopped d-c voltage  $U_s$ . The inverter 2 is coupled by a  
capacitor 3 to a transformer 4, which has a primary winding 5 and two secondary windings  
15 6a and 6b. The secondary windings 6a and 6b have different winding directions, so that given  
a positive voltage  $U_p$  on the primary winding 5 the voltage  $U_{sa}$  generated on the secondary  
winding 6a is also positive, whereas given a positive voltage  $U_p$ , the dropping voltage  $U_{sb}$   
on the secondary winding 6b is negative. The transformer 4 has a common transformer core  
both for the primary winding 5 and for the secondary windings 6a and 6b. A current flowing  
20 through the capacitor 3 in the primary winding 5 is denoted by  $I_c$ .

The secondary winding 6a is coupled by way of a diode  $D_a$  and an output filter  
 $F_a$  to an output 7a, on which an output voltage  $U_a$  is dropping. The secondary winding 6b is  
connected by a diode  $D_b$  and a filter  $F_b$  to an output 7b, on which an output voltage  $U_b$  is  
dropping. The converter 1 furthermore contains a feedback loop with a regulating circuit 8,  
25 which is coupled on the input side to the outputs 7a and 7b of the converter 1 and on the  
output side to the inverter 2. The regulating circuit 8 sets the frequency and the duty cycle of  
the voltage  $U_s$  supplied by the inverter 2 as a function of the voltages  $U_a$  and  $U_b$  present on  
the outputs 7a and 7b, in order to regulate the output voltages  $U_a$  and  $U_b$  to desired  
predefined voltage values.

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In the resonant converter 1, the capacitor 3, the main inductance and the  
leakage inductances of the transformer 4 constitute resonant circuit elements, which are  
induced to oscillate by the a-c voltage  $U_s$  and produce a corresponding behavior of the  
current  $I_c$  flowing into the circuit part that has the resonant circuit elements and of the  
voltage  $U_p$  dropping on the primary winding. In the case of positive voltage values of the

voltage  $U_p$ , a current  $I_a$  is generated, which flows through the diode  $D_a$  to the filter  $F_a$  for the time during which, in this operating state, the voltage  $U_{sa}$  exceeds the voltage present on the input of the filter  $F_a$  minus the diode forward voltage over the diode  $D_a$ . If the voltage  $U_p$  on the primary winding 5 has positive voltage values, no current is generated by the secondary winding 6b, since in this case the diode  $D_b$  blocks.

In the event of negative voltage values of the voltage  $U_p$  there is a positive voltage  $U_{sb}$  present on the secondary winding 6b and a negative voltage  $U_{sa}$  on the secondary winding 6a. In this case a current  $I_b$  is generated, which flows from the secondary winding 6b through the diode  $D_b$  to the output filter  $F_b$  for the period of time during which, in this operating state, the voltage  $U_{sb}$  exceeds the voltage present on the input of the filters  $F_b$  minus the diode forward voltage over the diode  $D_b$ .

Fig.2 shows a design variant of the inverter or chopper 2 in Fig. 1. A control signal 20, here represented by a pulse sequence, generated by the regulating circuit 8, is fed to a half-bridge drive circuit 21, which from the control signal 20 generates control signals 22 and 23 for the switching elements 24 and 25, which form a half-bridge circuit. The switching elements 24 and 25 are designed as MOSFET transistors. The control signals 22 and 23 are fed to gate connections (control connections) of the transistors 24 and 25. The inverter 2 converts a d-c voltage  $U_{DC}$  into the a-c voltage  $U_s$  by alternately switching the switching elements 24 and 25 on and off. The d-c voltage  $U_{DC}$  is generated, in power supply units/power packs/chargers, for example, from the a-c voltage of an a-c voltage mains by means of rectifiers.

Fig. 3A to 3C show design variants of the output filters  $F_a$  and  $F_b$  of the resonant converter 1. These have a connection A, which is connected to the diodes  $D_a$  and  $D_b$ . The connections B and C are connected to the outputs 7a and 7b of the converter 1. The filter according to Fig. 3 only contains a capacitor 30. The output filter according to Fig. 3B contains two capacitors 31 and 32 and an inductance 33. The output filter according to Fig. 3C contains a capacitor 34, an inductance 35 and a diode 36.

Fig. 4 shows an equivalent circuit diagram for the resonant converter 1 in Fig. 1, in which the transformer 4 has been replaced by a transformer equivalent circuit diagram. Here the electrical function of the transformer 4 may essentially be represented by a primary-side leakage inductance  $L_{rp}$ , a main inductance  $L_h$ , a secondary-side leakage inductance  $L_{rsa}$  for the secondary winding 6a and a secondary-side leakage inductance  $L_{rsb}$  for the secondary winding 6b. The filters  $F_a$  and  $F_b$  are here assumed as ideal and not shown, as is the regulating circuit 8. Loads  $R_a$  and  $R_b$  are connected to outputs 7a and 7b of the converter 1.

Figs. 5 to 7 show how it is possible to regulate the output voltages  $U_a$  and  $U_b$  by adjusting the frequency  $f_0$  and/or the cycle period  $t_0=1/f_0$  and the duty cycle of the a-c voltage  $U_s$ . The duty cycle is here determined by the period of time  $t_{sH}$  and  $t_{sL}$ , the upper switching element 24 being switched on and the lower switching element 25 being switched off during a period of time  $t_{sH}$ , and the upper switching element 24 being switched off and the lower switching element 25 being switched on during a period of time  $t_{sL}$ . The duty cycle is obtained as  $t_{sH}/t_0$ . The characteristics of the a-c voltage  $U_s$ , of the current  $I_c$  through the capacitor 3, of the current  $I_a$  through the main inductance  $L_a$  of the transformer 4, of the current  $I_a$  delivered by the secondary winding 6a and of the current  $I_b$  delivered by the secondary winding 6b are represented for each of two periods of time  $t_0$ . All winding ratios in the underlying example according to the equivalent circuit in Fig. 4 are in each case assumed to be one; in addition,  $L_{rsa}$  is here equal to  $L_{rsb}$ .

Fig. 5 shows the operating state in which the frequency  $f_0=1/t_0$  is set to 1.47 times  $f_r$ ,  $f_r$  being the resonant frequency of the converter 1 and being approximately determined as

$$f_r = \frac{1}{2\pi} \sqrt{\frac{1}{C(3)[L_{rp} + L_h]}}$$

$C(3)$  being the capacitance of the capacitor 3. In the operating instance according to Fig. 5 the duty cycle is selected as 50%. In this operating state the current characteristics of  $I_a$  and  $I_b$  are generated with virtually identical half-waves during the time periods  $t_{sH}$  and  $t_{sL}$  respectively. In the operating state according to Fig. 6 the frequency  $f_0=1/t_0$  is increased 1.53 times  $f_r$ . The duty cycle is reduced to 40%. The characteristic of the current  $I_a$  has remained virtually identical to the operating state in Fig.5. The characteristic of the current  $I_b$  now has half-waves with reduced amplitude, so that the power carried to the output 7b by the secondary winding 6b is reduced. Fig. 7 shows an operating instance with a frequency  $f_0=1/t_0$  equal to 1.55 times  $f_r$  and a duty cycle of 65%. In this operating instance the current  $I_a$  is essentially reduced to zero and the amplitude of the half-waves of  $I_b$  increased in comparison to Fig. 6, so that in this operating instance the secondary winding 6a carries no power to the output 7a but, in comparison to Fig. 6, secondary winding 6b carries increased power to output 7b.

The examples of operating states according to Figs 5 to 7 show that with the converter circuit according to the invention a highly variable adjustment to different loads of

the various converter outputs is possible. With the converter according to the invention it is possible, in particular, to achieve small tolerances of the output voltages even in the case of low output voltages and high output currents.

Fig. 8 and 9 show variants of the converter 1 in Fig. 1, which are denoted by 1' and 1". In both variants the two secondary windings 6a and 6b are electrically coupled to one another; in this instance these are connected to a common ground potential. In the development of the converter 1 according to Fig. 1 the secondary windings 6a and 6b are electrically separated from one another. In Fig. 8, moreover, as a further variant an additional external inductance L1 is provided, which is arranged on the primary side of the transformer 4 between the capacitor 3 and the primary winding 5 and acts as an additional inductive resonant circuit element in addition to the inductances of the transformer 4. In the given type of transformer 4 with specific transformer inductances this additional inductance enables the resonance frequency of the converter to be adjusted. Fig. 9 shows additional external inductances L2a and L2b on the secondary side of the transformer 4. The inductance L2a is arranged between the secondary winding 6a and the diode Ta, the inductance L2b lies between the secondary winding 6b and the diode Db. These two inductances also act as additional circuit elements and can be used to adjust the desired – possibly asymmetrical – power distribution between the outputs in rating, for instance. Converter variants are obviously also possible in which additional external inductances are provided both on the primary side of the transformer 4 and on the secondary side of the transformer 4.

Fig.10 shows a converter variant 1''' with a larger number of converter outputs. In this instance the converter has four converter outputs. In addition to the primary winding 5 the transformer 4 now has two groups of secondary windings with different winding direction (indicated by the letters a and b), which contain the secondary windings 6a1 and 6a2 on the one hand and the secondary windings 6b1 and 6b2 on the other. The secondary windings are connected by diodes Da1, Da2, Db1 and Db2 with output filters Fa1, Fa2, Fb1 and Fb2 to the converter outputs, which carry output voltages Ua1, Ua2, Ub1 and Ub2. The output voltages Ua1 and Ub1 are fed to the regulating circuit 8 as measured variables. The regulating circuit 8 therefore in this case analyzes two output voltages, the one output voltage Ua1 being generated by the secondary winding 6a1 from the group of secondary windings with the first winding direction. The other output voltage Ub1 fed to the regulating circuit 8 is assigned to the secondary winding 6b1 from the group of secondary windings having the opposite winding direction. Here therefore, a measured variable, i.e. output voltage, is analyzed for each of the two groups having secondary windings of different winding directions and used

for regulating purposes. This represents a particularly simple and effective method of regulating the output voltages of the converter.

Fig. 11 shows that as measured variables the regulating circuit analyzes either the actual voltages on the converter outputs or the voltages on the connected load of the converter, the latter being reduced, compared to the corresponding output voltages, owing to voltage drops on the leads between the converter and the loads. Examples of both variants are represented in Fig. 11. The converter outputs here carry the two output voltages  $U_a$  and  $U_b$ , to each of which a load  $R_a$  and a load  $R_b$  is connected. The connecting leads between the converter output supplying the output voltage  $U_a$  and the load  $R_a$  are represented here by a block 31. The connecting leads between the output of the converter supplying the output voltage  $U_b$  and the load  $R_b$  are represented by the block 32.

Fig. 12 shows an example of embodiment of the regulating circuit 8. A first measuring signal  $V_a$  and a second measuring signal  $V_b$ , which correspond to output voltages  $U_a$  and  $U_b$  and  $U_{a1}$  and  $U_{b1}$  respectively, are fed to the two inputs of the regulating circuit. The measuring signals  $V_a$  and  $V_b$  are compared with reference signals  $V_{ref}$  and  $V_{bref}$ . Subtractors 100 and 101 are used in this. The subtractor 100 delivers the difference  $V_{ref} - V_a$  to a circuit block 102. The subtractor 101 delivers the difference  $V_{bref} - V_b$  to a circuit block 103. The circuit blocks 102 and 103 contain amplifiers and scaling circuits, so that the difference signal supplied by the subtractor 100 is multiplied by a factor  $K_A$  and the difference signal supplied by the subtractor 101 by a factor  $K_B$ . Here in this example of embodiment the following relationship applies:

$$k_A \cdot V_{ref} \cong k_B \cdot V_{bref}$$

The output signals from the circuit blocks 102 and 103 are further processed by an adder 104 and a subtractor 105. The adder 104 adds the output signals from the circuit blocks 102 and 103 and delivers its output signal to a frequency controller 106, which is designed, for example, as PID controller. The difference signal delivered by the subtractor 105 is fed to a duty cycle controller 107, which is also designed, for example, as PID controller. A signal generator circuit 108 now generates the control signal 20 supplied to the inverter 2 by the regulating circuit 8, the control signal here being a pulse width modulated signal. The frequency of the signal 20, which determines the frequency of the a-c voltage  $U_s$  of the resonant converter, is adjusted by the output signal of the frequency controller 106.

The duty cycle of the signal 20, which determines the duty cycle of the a-c voltage  $U_s$ , is adjusted by the duty cycle controller 107.

If the value of the measuring signal  $V_a$ , for example, is reduced in the regulating circuit according to Fig. 12, so that  $V_a$  becomes  $< V_{ref}$ , this leads on the one  
5 hand to a reduction of the frequency set by the controller 106 and hence, according to the behavior of the resonant converter, to a tendency to increase on the part of the output voltages generated by the resonant converter. On the other hand, however, the control produced in this case also causes a reduction of the duty cycle of the signal 20 and the a-c voltage  $U_s$  determined by the controller 107. This occurs, for example, in the operating state  
10 according to Fig. 6, where the power carried to the output 7a by the secondary winding 6a is increased in relation to the power carried to the output 7b by the secondary winding 6b.

If in another instance, for example, the measuring signal  $V_b$  or the corresponding output voltage  $U_b$  is reduced, this likewise leads to a reduction of the frequency of the signals 20 or the frequency of the a-c voltage  $U_s$ . In this case, however, the  
15 controller 107 brings about an increase of the duty cycle of the signal 20 and the duty cycle of the a-c voltage  $U_s$ , so that in this operating instance the power distribution is modified so that the power carried to the output 7b is increased in comparison to the power carried to the output 7a. The control characteristic also applies analogously to the design variants having more than two converter outputs.